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(54) **METHOD FOR ADJUSTING A PROJECTION OBJECTIVE**

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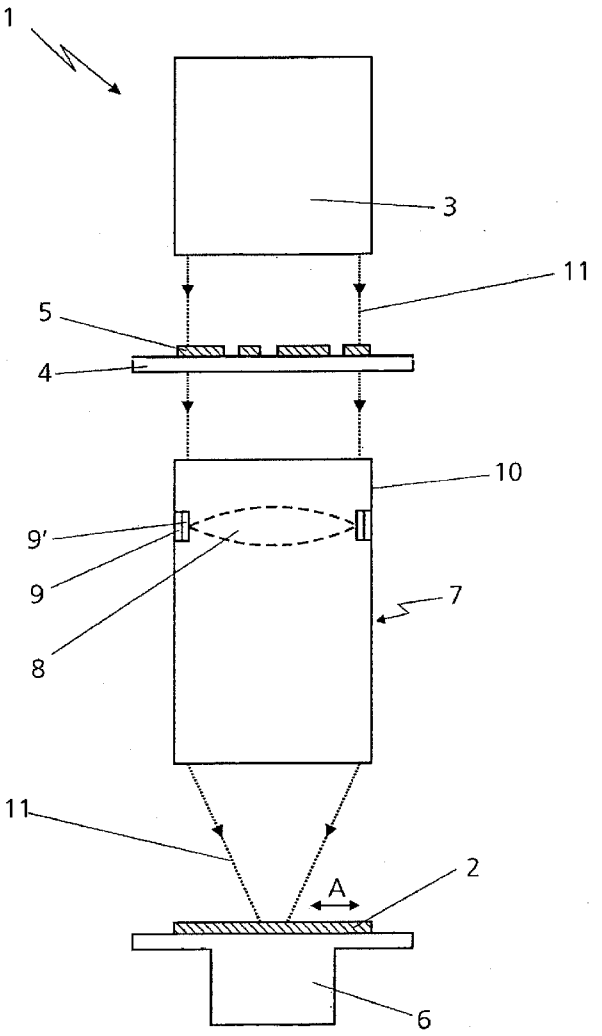
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(57) **ABSTRACT**

A projection objective having a number of adjustable optical elements is optimized with respect to a number of aberrations by specifying a set of parameters describing imaging properties of the objective, each parameter in the set having an, absolute value at each of a plurality of field points in an image plane of the projection objective. At least one of the optical elements is adjusted such that for each of the parameters in the set, the field maximum of its absolute value is minimized.



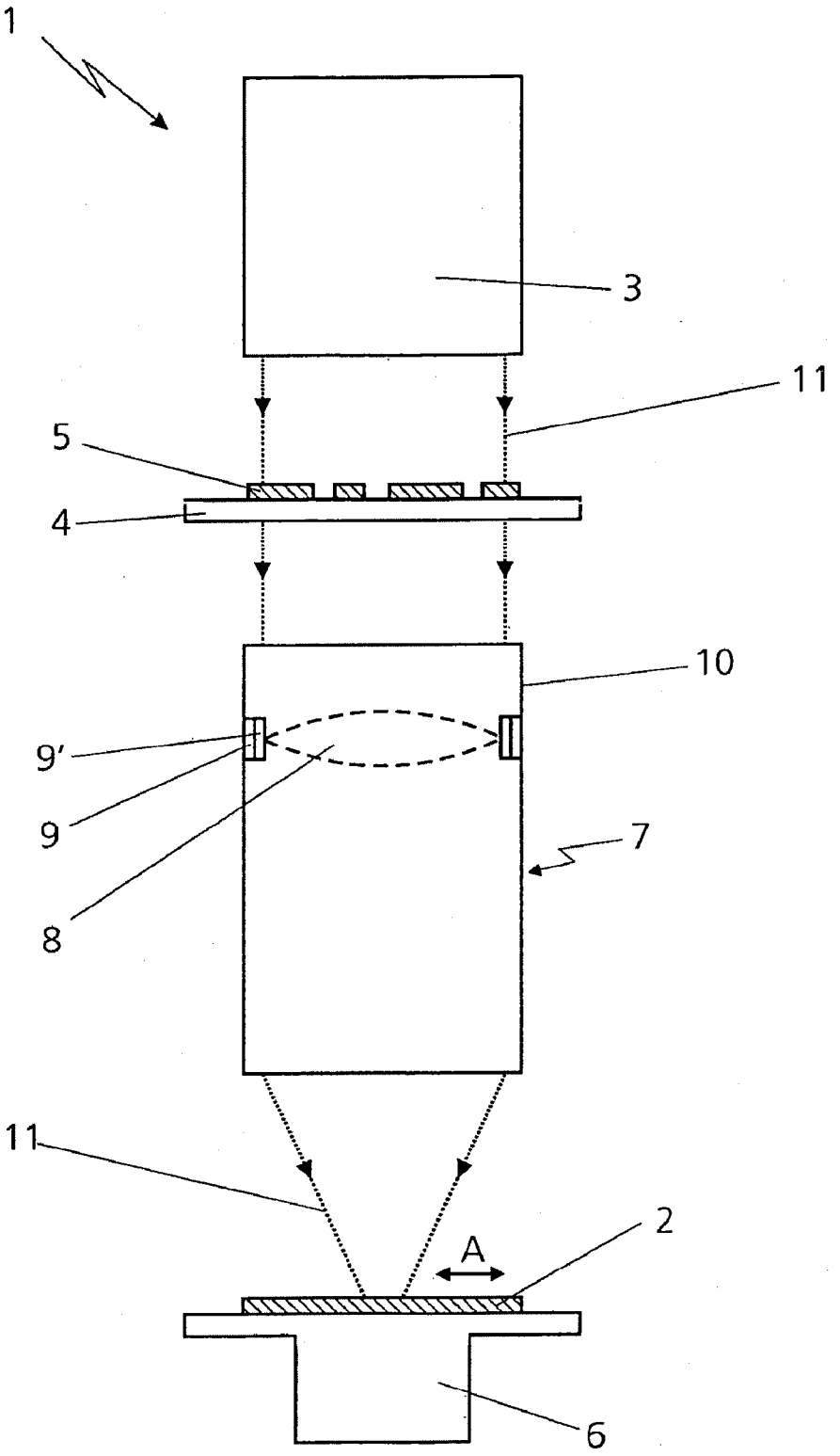


Fig. 1

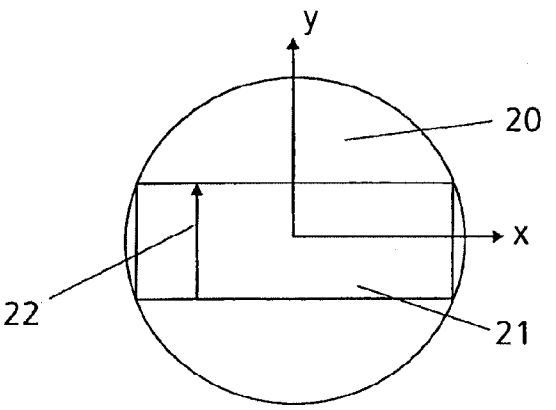


Fig. 2

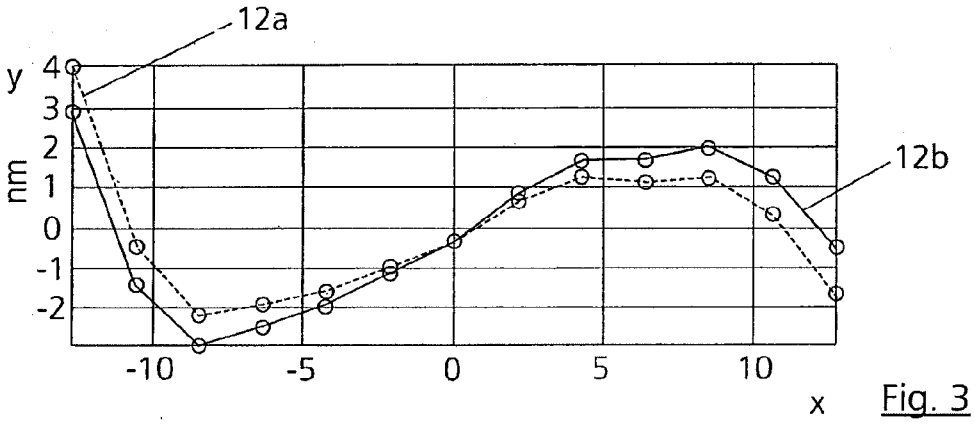


Fig. 3

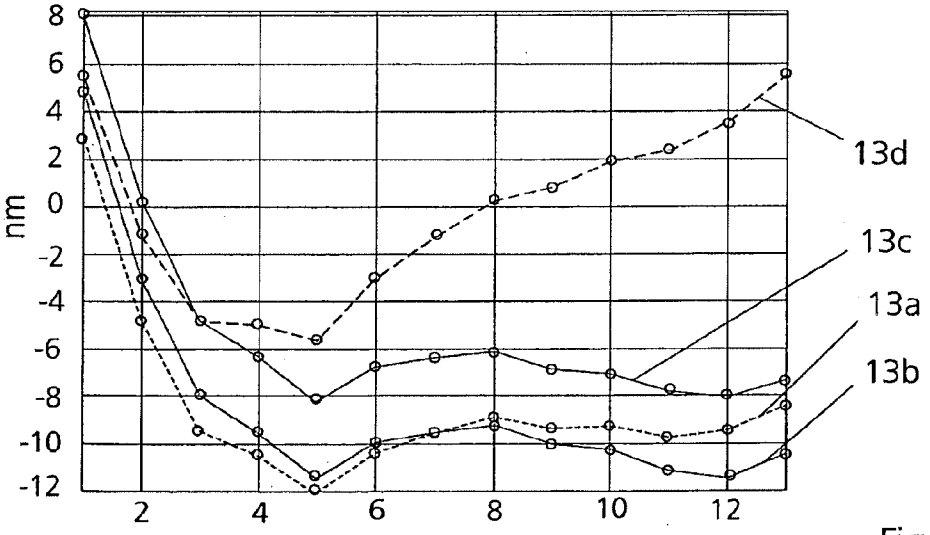


Fig. 4

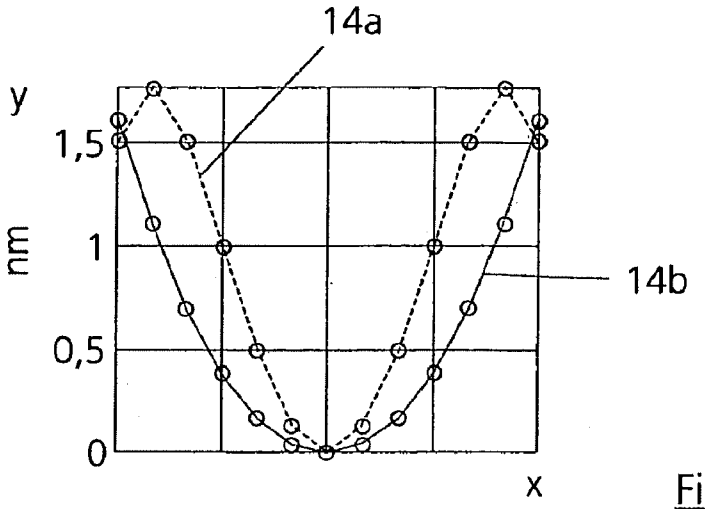


Fig. 5

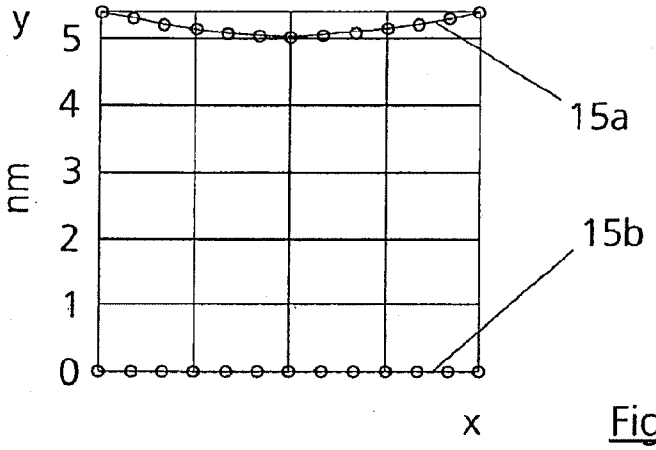


Fig. 6

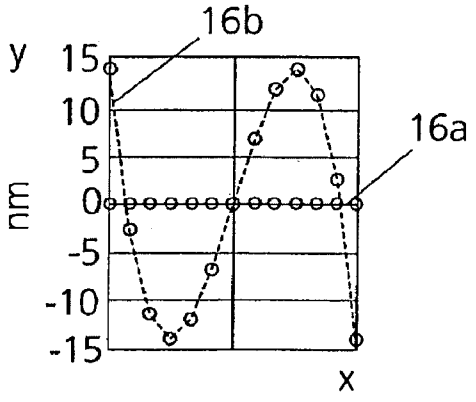


Fig. 7

METHOD FOR ADJUSTING A PROJECTION OBJECTIVE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This is a continuation of, and claims priority under 35 U.S.C. §120 to, U.S. application Ser. No. 11/102,102 filed Apr. 8, 2005 which, in turn claims priority under 35 U.S.C. §119(e) to U.S. Provisional Application Ser. No. 60/560,623 filed Apr. 9, 2004 and under 35 U.S.C. §119 to German Patent Application No. DE 10 2004 035 595.9 filed Jul. 22, 2004.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The invention relates to a method for adjusting a projection objective of a projection exposure machine for microlithography for the purpose of fabricating semiconductor components having a number of optical elements, which can be set via manipulators, for simultaneously minimizing a number of aberrations of the projection objective, the minimization of the aberrations being carried out by manipulating at least one portion of the optical elements with the aid of their respective manipulators.

[0004] 2. Description of the Prior Art

[0005] EP 1 231 516 A2 discloses a method for specifying, fabricating and adjusting a projection objective. For the specification, that is to say the description of the optical properties of the projection objective, use is made in this case of a description of the transmission function of the objective pupil for a number of field points. Field points represent a specific position in the object or image plane of the projection objective. The scalar transmission function of the objective pupil can be specified for each field point in the form of a two-dimensional complex variable. The phase of this complex variable is also denoted wave aberration. EP 1 231 516 A2 describes these wave aberrations for each field point by means of so-called Zernike coefficients. Consequently, the image-forming properties of the projection objective are likewise specified by the specification of these Zernike coefficients.

[0006] In order to ensure optimum use of the projection objective in a projection exposure machine for microlithography, for example for the purpose of fabricating semiconductor components, the above-described specification of the image-forming properties of the projection objective is very important although, of course, in addition to accurate knowledge relating to the lithographic process to be carried out with the aid of the projection exposure machine (illumination, precision of the structures to be exposed, photo-resist process, etc.). In general, it is not only a single lithographic process which is relevant, but rather it must even be possible to carry out a multiplicity of various lithographic processes with the aid of the projection objective. In order for it to be possible to find a relationship between this multiplicity of lithographic processes and the properties of the projection objective, their most general description of the image-forming properties of the projection objective is sensible.

[0007] The relationship between the objective properties and the lithographic process is established in EP 1 231 516 A2 with the aid of these Zernike coefficients. This can be accomplished in many cases with the aid of a linear model, given the assumption of sufficiently small aberrations.

[0008] Following on from the fabrication of a projection objective, a concluding optimization by means of the manipulators (xy-manipulation, tilt manipulation, z-manipulation, wavelength, gas pressure or reticle tilt and reticle height) of the optical elements located in the projection objective is important in deciding the final image forming quality or the image-forming properties of the projection objective.

[0009] It is known to introduce slight changes in the optical properties by measuring parameters for which the effects of the manipulation for the optical elements on these parameters are known, whereupon optimization of the parameters is carried out. As described at the beginning, Zernike coefficients which describe the image-forming properties of the projection objective are determined as a rule for this purpose from measured values. This is achieved, for example, by means of measurements at a number of field points in the field, relevant for lithographic imaging, in the image plane of the projection objective. Zernike coefficients with designations Z_2 to Z_{37} are determined in this way (compare EP 1 231 516 A2), after which the optimization is performed. The average root-mean-square deviation of all the measured field points from 0 is minimized for this purpose in the case of each Zernike coefficient (so-called least square optimization).

SUMMARY OF THE INVENTION

[0010] The present invention is based on the object of further improving a method of the type mentioned at the beginning; in particular, the aim is to specify the image-forming properties of the projection objective as faithfully as possible to reality.

[0011] This object is achieved according to the invention by virtue of the fact that the adjustment is carried out by means of min-max optimization of a number of parameters, suitable for describing the imaging properties of the projection objective, at various field points of an image plane of the projection objective, as a result of which the individual parameters are optimized in such a way that the parameter value of the field point which has the maximum aberration is optimized, that is to say is generally minimized or at least reduced.

[0012] The min-max optimization is also denoted synonymously as minimax optimization.

The measures according to the invention provide greatly improved concepts for adjusting lithography objectives and for optimizing their manipulators. The use of the nonlinear min-max optimization is advantageous in particular when the field maximum of the Zernike coefficients is used to specify the image-forming quality of the projection objective, since the min-max optimization optimizes precisely this field maximum. A min-max optimization of a projection objective is understood to be the optimization of a set of parameters at various field points in the image plane of the projection objective. Each individual parameter is optimized in this case such that the worst value of all the field points is optimal. Since it is not initially established at which field point this worst value occurs, this optimization is a nonlinear method for whose solution known numerical methods can be used. The various parameters can feature in the optimization with different weightings. Moreover, it is possible to introduce secondary conditions in order, for example, to limit the maximum traverse paths of the manipulators. It is conceivable, furthermore, to combine a number of field points, in which case a parameter at a field point is replaced by a function of this parameter at a number of field points.

[0013] Possible as parameters are, for example, individual Zernike coefficients to describe the wave aberrations in the objective pupil.

[0014] Also conceivable as parameter is a linear combination of Zernike coefficients which describes lithographically important variables such as distortion or structure width.

[0015] Advantageous refinements and developments of the invention follow from the dependent claims. Exemplary embodiments are described in principle below with the aid of the drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. **1** shows a schematic representation of a projection exposure machine for microlithography which can be used to expose structures on wafers coated with photosensitive materials;

[0017] FIG. **2** shows an illustration of a scanner slit within a full image plane of a projection objective;

[0018] FIG. **3** shows a graph of a Zernike coefficient Z_7 after a tilt optimization with the aid of z-manipulators;

[0019] FIG. **4** shows a graph of a profile of an optimization of an astigmatism aberration;

[0020] FIG. **5** shows a graph of a profile of a Zernike coefficient Z_2 with and without joint optimization of reticle tilt and xy-manipulation;

[0021] FIG. **6** shows a graph of a profile of a Zernike coefficient Z_7 with and without joint optimization of reticle tilt and xy-manipulation; and

[0022] FIG. **7** shows a graph of a distortion for annular and for coherent illumination setting.

DETAILED DESCRIPTION

[0023] FIG. **1** illustrates a projection exposure machine **1** for microlithography. This serves for exposing structures on a substrate coated with photosensitive materials and which in general overwhelmingly comprises silicon and is denoted as a wafer **2** for fabricating semiconductor components such as, for example, computer chips.

[0024] The projection exposure machine **1** essentially comprises in this case an illumination device **3**, a device **4** for accommodating and exactly positioning a mask provided with a grid-like structure, a so-called reticle **5** which is used to determine the later structures on the wafer **2**, a device **6** for holding, moving and exactly positioning this very wafer **2**, and an imaging device, specifically a projection objective with a number of optical elements such as, for example, lenses **8**, which are supported by mounts **9** and/or manipulators **9'** in an objective housing **10** of the projection objective **7**.

[0025] The fundamental functional principle provides in this case that the structures introduced into the reticle **5** are imaged in a demagnified fashion onto the wafer **2**.

[0026] After exposure has been performed, the wafer **2** is moved on so that a multiplicity of individual fields each having the structure prescribed by the reticle **5** are exposed on the same wafer **2**.

[0027] The illumination device **3** provides a projection beam **11**, for example light or a similar electromagnetic radiation, required for imaging the reticle **5** onto the wafer **2**. A laser or the like can be used as source for this radiation. The radiation is shaped in the illumination device **3** via optical elements (not illustrated) such that when impinging onto the reticle **5** the projection beam **11** has the desired properties as regards diameter, polarization, coherence and the like. The spatial coherence is in this case a measure of the angular spectrum of the radiation in the reticle plane. This parameter can be varied by the setting of various illumination settings.

[0028] An image of the structures of the reticle **5** which are introduced is produced via the projection beam **11** and transferred onto the wafer **2** in an appropriately demagnified fashion by the projection objective **7**, as already explained above. The projection objective **7** has a multiplicity of individual refractive, diffractive and/or reflective optical elements such as, for example, lenses **8**, mirrors, prisms, plane-parallel plates and the like, only the lens **8** being illustrated.

[0029] After the fabrication, a concluding optimization of the manipulators of the optical elements, in particular the lenses **8**, the reticle tilt/reticle height and the wavelength is essential in deciding the final image-forming quality of the projection objective **7**. In this case, the image-forming quality of the projection objective is optimized, inter alfa, taking account of the following aberrations: distortion, field curvature, astigmatism, coma, spherical aberration and wavefront errors of higher order.

[0030] It is known from the prior art to introduce slight changes in the optical properties by measuring parameters in the case of which the effects of the manipulation of the optical elements on these parameters are known, whereupon optimization of the parameters is carried out. As a rule, Zernike coefficients which describe the image-forming properties of the projection objective are determined for this purpose from measured values. This is achieved, for example, by measurements at a number of field points via an imaging scanner slit (=field in the image plane which is relevant to lithographical imaging). As described, for example, in EP 1 231 516 A2, Zernike coefficients with designations Z_2 to Z_{37} are determined in this way, after which the optimization is performed. For this purpose, the average root-mean-square deviation of all the measured field points from 0 is minimized for each Zernike coefficient (so-called least square optimization). Subsequently, the Zernike coefficients Z_2 to Z_9 are represented by their corresponding function terms. Zernike coefficients of higher order are described in EP 1 231 516 A2.

Zernike coefficient Z_n	Function term f_n
Z_2	$\rho \times \cos(\phi)$
Z_3	$\rho \times \sin(\phi)$
Z_4	$2 \times \rho^2 - 1$
Z_5	$\rho^2 \times \cos(2\phi)$
Z_6	$\rho^2 \times \sin(2\phi)$
Z_7	$(3\rho^3 - 2\rho) \times \cos(\phi)$
Z_8	$(3\rho^3 - 2\rho) \times \sin(\phi)$
Z_9	$6\rho^4 - 6\rho^2 + 1$

[0031] It is likewise known to use these Zernike coefficients to find the relationship between the objective properties and the lithographic process. Assuming sufficiently small aberrations, this can be accomplished in many cases with the aid of a linear model:

$$L_i = a_2 \times Z_2(i) + a_3 \times Z_3(i) + \ldots + a_n \times Z_n(i)$$

[0032] The weighted sum can be truncated after a sufficient number of terms, since in most cases the weighting factors become small very rapidly with rising Zernike number n. Of course, it is also possible to include square terms or terms of even higher order. The weighting factors a_n can be determined experimentally or by simulation.

[0033] The variable L_i describes a parameter of the lithographic process at the field point i. L_i can be, for example, a horizontal offset of a structure relative to its ideal position (distortion), or else the deviation from an ideal line width.

[0034] The fabrication or optimization of a projection objective **7** firstly requires knowledge of the critical lithographic process for which the projection objective **7** is later to be used. It is then possible to calculate the appropriate weighting factors a_n for various Zernike coefficients from this information. Maximum absolute values can then be derived for various Zernike coefficients from the prescription as to how far various L_i may be maximized.

[0035] During optimization of the projection objective **7**, various Zernike coefficients are then minimized at various field points, it being possible for these also to be various L_i in a specific instance. Projection objectives **7** are then also usually specified such that various Zernike coefficients and/or various L_i may not exceed a maximum absolute value for a specific number of field points. It is thereby ensured that the image-forming properties of the projection objective **7** suffice for a representative selection of lithographic processes.

[0036] FIG. **2** shows the round full image field **20** of the projection objective **7**. All the points on the reticle **5** which lie within this region can be imaged onto the wafer **2** with the aid of the projection objective **7**. When the projection exposure machine **1** is used as scanner, it is only a rectangular section, the so-called scanner slit **21**, from the full image field **20** that is used. During a lithographic exposure with the aid of a scanner, the reticle **5** and the wafer **2** are moved simultaneously during imaging in a plane perpendicular to the optical axis. The consequence of this is that a point on the reticle **5** is imaged by various field points of the projection objective **7**. The aberrations relevant to this imaging are therefore the aberrations of all the field points which lie on a straight line in the scanner slit **21** which is orientated in the scanning direction (indicated by arrow **22**). In order to describe the image-forming properties of the projection objective **7** in a scanner, the relevant parameters such as, for example, Zernike coefficients, are not specified for individual field points, but averaged over all the field points in the scanning direction. It is also possible to introduce a weighting during this averaging in order to take account of different intensities of illumination in the course of the scanning operation. The parameters averaged in such a way are referred to as being scanner integrated.

[0037] FIGS. **3** to **7** illustrate profiles of Zernike coefficients Z_2 and Z_7 over a number of field points which describe the aberrations and which, for their part, are determined at various field points in the scanner slit **21** of the projection objective **7**. Plotted respectively on the x-axis is the x-position in the scanner slit **21**, while the y-axis respectively specifies the y-deviation of the respective Zernike coefficient from 0 in nm.

[0038] Various manipulators of the projection objective **7** are moved during the optimization of the image-forming properties. These manipulators can be subdivided into two classes with the aid of the symmetry of the induced aberrations:

[0039] 1. Manipulators for optimizing tunable aberrations:
Tunable aberrations are changes in various Zernike coefficients at various field points, the induced changes being invariant under an arbitrary rotation about the optical axis (z-axis).
The following come into consideration in this case as manipulators:

[0040] displacement of lenses **8** or reticle **5** along the optical axis;

[0041] change in temperature and atmospheric pressure;

[0042] change in wavelength; and

[0043] change in the composition of the purge gas surrounding the lenses **8**.

[0044] 2. Manipulators for optimizing centrable aberrations:
Centrable aberrations are changes in various Zernike coefficients at various field points, the induced changes in the plane perpendicular to the optical axis having a marked axis of symmetry. The following come into consideration in this case as manipulators:

[0045] displacement of lenses **8** perpendicular to the optical axis; and

[0046] tilting of lenses **8** or reticle **5** about an axis perpendicular to the optical axis.

[0047] It is known from the Seidel aberration theory that small changes in tunable aberrations always have the same field distribution for a specific Zernike coefficient. This fundamental "shape" of the aberrations is independent of the type of manipulator. An equivalent theoretical model exists for centrable aberrations.

[0048] The following table shows the tunable and centrable aberrations of lowest order, the tunable aberrations presented here corresponding to the third order Seidel aberrations. The centrable aberrations refer in this case to an x-decentering, this corresponding, however, to a displacement of the lens **8** along the x-axis. For decenterings along another axis, it is necessary to rotate the field profiles (with coordinates r, ϕ in the field for lithographic imaging) correspondingly.

Zernike coefficient Z_n	Type of aberration	Tunable profile	Centrable profile
Z_2	distortion	$r \times \cos(\phi)$	r^2
Z_3	distortion	$r \times \sin(\phi)$	
Z_4	image surface	r^2	
Z_5	astigmatism	$r^2 \times \cos(\phi)$	$r \times \cos(\phi)$
Z_6	astigmatism	$r^2 \times \sin(\phi)$	$r \times \sin(\phi)$
Z_7	coma	$r \times \cos(\phi)$	r^0
Z_8	coma	$r \times \sin(\phi)$	
Z_9	spherical aberration	r^0	$r \times \cos(\phi)$

[0049] As an example, FIG. **3** shows a profile of a Zernike coefficient Z_7 of a projection objective **7**. The tilt of this profile can be set by z-manipulators. In accordance with the prior art, the optimum tilt is achieved by means of a least square optimization, that is to say the root-mean-square value of the Zernike coefficient Z_7 is minimized over all the field points. When, however, the field maximum (=maximum absolute value of a Zernike coefficient at all the field points in the scanner slit **21**) is used to specify the projection objective **7**, it is advantageous for precisely this field maximum to be set as small as possible. This is achieved by means of a nonlinear min-max optimization.

[0050] As may be seen from FIG. **3**, the field maximum in accordance with a least square optimization (curve **12***a*) can be substantially larger than in accordance with a min-max optimization (curve **12***b*). The inventor has established that performance with regard to the Zernike coefficients Z_7 and Z_9

can be improved by more than half a nanometer in a significant number of cases for the projection objectives **7** solely by changing from least square optimization to min-max optimization. It was possible here for the field maximum to be lowered from 4.06 nm (least square optimization) to 2.92 nm (min-max optimization).

[0051] FIG. **4** shows a joint optimization of centrable and tunable aberrations. The joint optimization of centrable and tunable aberrations on the projection objective **7** instead of a sequential procedure additionally permits a more accurate and speedy optimization of the optical image-forming properties of the projection objective **7**. A profile of a Zernike coefficient Z_7 (coma) whose tunable component (tilt) and centrable component (offset) are minimized with the aid of a min-max optimization was selected as an example. The simultaneous optimization of tilt and offset here delivers a substantially better result than the sequential min-max optimization of tunable aberrations with the aid of z-manipulators, and subsequent optimization of centrable aberrations with the aid of xy-manipulators. A curve **13***a* shows the uncorrected Z_7 profile here. A curve **13***b* is the Z_7 profile with optimized tilt. A curve **13***c* shows the Z_7 profile with optimized tilt and offset (optimized sequentially one after another). As may further be seen from FIG. **4**, a simultaneous optimization of the field maximum with the aid of z-manipulators (tilt) and xy-manipulators (offset) is the most advantageous (curve **13***d*), in which case the field maximum of 8.2 nm can be lowered to 5.6 nm in contrast with the sequential method.

[0052] FIG. **5** shows the effect of a reticle tilt (curve **14***a*) or of a movement of the xy manipulator (curve **14***b*) on a profile of the Zernike coefficient Z_2. FIG. **6** shows the effect of a reticle tilt (curve **15***b*) or of a movement of the xy manipulator (curve **15***a*) on a Z_7 profile. A Z_2 offset, which corresponds to the curve **14***a*, could be removed in the case of the above-described scenario by means of a reticle tilt. However, when the Z_7 offset corresponding to the curve **15***a* is removed by the xy-manipulator in a second step, a Z_2 error is introduced again into the objective (curve **14***b*). In the case of a 10 nm Z_7 offset, this would result nevertheless in an additional Z_2 error of more than 3 nm. This could be avoided by means of an orthogonalized concept of xy-manipulators and reticle tilt, for which purpose it would be necessary to treat the reticle tilt like any other xy-manipulator.

[0053] It is advantageous to apply a distortion optimization dependent on the illumination setting of the projection objective **7**. The distortion values can be substantially improved in specific cases by tracking the manipulators during changing of the illumination setting (for example from annular to coherent). A geometrical distortion (Z_2) is usually not optimized, but a combination of geometrical distortion and coma-induced distortion. All the scanner-integrated Zernike coefficients vanish here, with the exception of Z_7, the Z_7 profile including higher tunable components. In the case of the present optimization with the aid of z-manipulators, a Z_2-component in the projection objective **7** is then increased so that the resulting distortion results in an annular illumination setting of 0 (curve **16***a* in FIG. **7**). In the event of a change in setting from annular to coherent, however, the result in this case is distortion values of up to approximately 15 nm (curve **16***b*). It is therefore proposed according to the invention to track the xy-and z-manipulators (including wavelength and reticle) during each change in illumination setting.

What is claimed is:

1. A method for adjusting a projection objective of a projection exposure machine of the type used for microlithography in the fabrication of semiconductor components and having an illumination device for providing an illumination beam and a plurality of optical elements in the path of the illumination beam for projecting an image onto a substrate, at least some of the optical elements being capable of being adjusted for altering aberrations of the projection objective, said method comprising the steps of:

(a) establishing an initial polarization of the illumination device;

(b) adjusting the projection objective with respect to at least one of the aberrations under initial polarization;

(c) changing the polarization of the illumination device from said initial polarization to a different polarization; and

(d) adjusting the projection objective with respect to said at least one aberration based on said different polarization.

2. The method of claim **1** wherein at least one of said adjusting steps comprises the step of satisfying a condition relating to an absolute value of at least one parameter of a set of parameters, each parameter in said set being a parameter representing respective imaging property of the projection objective and having an absolute value at each of a plurality of points in a field of an image plane of the projection objective.

3. The method of claim **2** wherein said condition is a condition requiring reduction of the absolute value of each parameter in said set at the one of said plurality of points in said field at which said absolute value is a maximum.

4. The method of claim **2** wherein said condition is a condition requiring minimization of the absolute value of each parameter in said set at the one of said plurality of points in said field at which said absolute value is a maximum.

5. The method of claim **2** wherein said adjusting step is carried out using a nonlinear numerical method.

6. The method of claim **2** wherein one of said absolute values is a maximum of all of said absolute values of all of said parameters and said condition is a condition requiring reduction of said maximum of all of said absolute values of all of said parameters.

7. The method of claim **2** wherein one of said absolute values is a maximum of all of said values of all of said parameters and said condition is a condition requiring minimization of said maximum of all of said absolute values of all of said parameters.

8. The method of claim **2** wherein said adjusting step is carried out using a nonlinear numerical method.

9. The method of claim **2** further comprising the steps of changing an illumination setting of the illumination device after said adjusting step has been carried out, and thereafter repeating said adjusting step.

10. The method of claim **9** wherein said illumination setting comprises a setting selected from the group consisting of a coherence setting, a diameter setting, and a polarization setting.

11. The method of claim **2** wherein at least one of said parameters comprises individual Zernike coefficients describing wave aberrations of an objective pupil of the projection objective.

12. The method of claim **2** wherein at least one of said parameters comprises a linear combination of Zernike coefficients.

13. The method of claim **2** wherein at least one of said parameters comprises an average of Zernike coefficients over a plurality of field points lying within a portion of the image plane defined by a scanner slit, said plurality of points lying along a line oriented in a scanning direction.

14. The method of claim **2** wherein said average is a weighted average.

15. The method of claim **2** wherein said set of parameters is a set which includes at least one parameter selected from the group consisting of distortion and line width.

16. The method of claim **2** wherein said set of parameters includes at least one parameter describing a centrable aberration, and said adjusting step comprises the step of tilting a reticle of the projection objective to adjust for said centrable aberration.

17. The method of claim **16** wherein said adjusting step comprises at least one of the following steps:

(i) displacing at least one of the optical elements in a direction perpendicular to an optical axis of the projection objective, and

(ii) tilting at least one of the optical elements in a direction perpendicular to said optical axis of the projection objective.

18. The method of claim **16** wherein said set of parameters further includes at least one parameter describing a tunable aberration, and said adjusting step comprises the step of adjusting at least one of the optical elements to adjust for said tunable aberration and said centrable aberration jointly.

19. The method of claim **18** wherein said adjusting step comprises at least one of the following steps:

(i) displacing at least one of the optical elements in a direction along the optical axis of the projection objective;

(ii) changing the wavelength of illumination of the projection objective;

(iii) changing a temperature within the projection objective;

(iv) changing an air pressure within the projection objective; and

(v) changing the composition of a purge gas surrounding the optical elements.

* * * * *